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(71) Applicant *(for all designated States except US)*: IMPLANT SCIENCES CORPORATION [US/US]; 107 Audubon Road #5, Wakefield, MA 01880–1246 (US).

(72) Inventor; and

(75) Inventor/Applicant *(for US only)*: ARMINI, Anthony, J. [US/US]; 5 Skytop Drive, Manchester–by–the–Sea, MA 01944 (US).

(74) Agents: CAMPBELL, Paula, A. et al.; Foley, Hoag & Eliot, LLP, One Post Office Square, Boston, MA 02109 (US).

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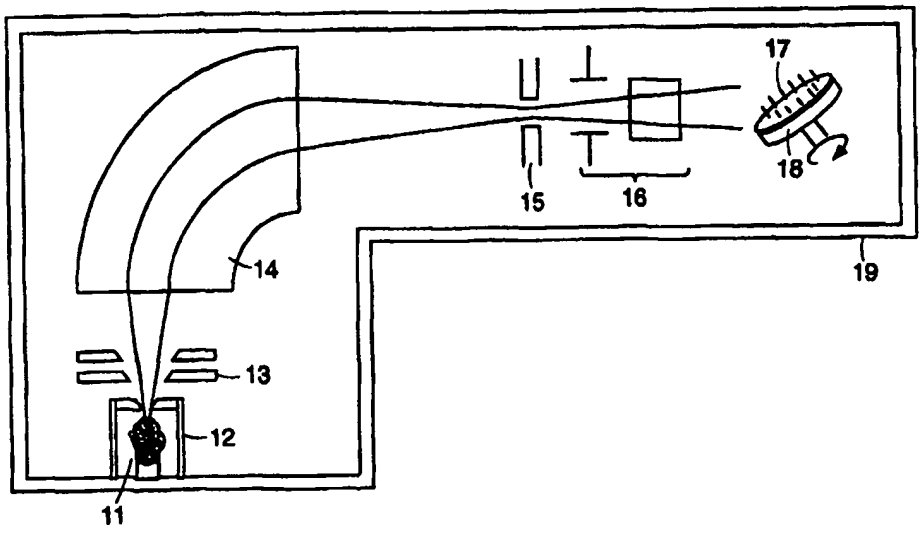

(57) Abstract

Past techniques utilized wet chemistry to produce a carrier–free radioisotope for a seed implant. However, by using the technique of ion implantation, it is possible to physically separate the precursor isotope by magnetic means and further, to physically direct a beam of these isotopically pure atoms and to embed them into a suitable carrier body. Thus, formation of the seed implant may be accomplished using dry techniques, that is, no liquid chemistry. The systems and methods disclosed herein are designed to produce a beam of a single stable isotope using an ion implanter and to further implant this single stable isotope below the surface of a carrier body. After neutron activation, these single stable isotopes will produce the isotopes iodine–125, palladium–103, cesium–131, or ytterbium–169 embedded within the carrier body. Optionally, the carrier body may be encapsulated prior to activating the precursor isotope embedded in the carrier body.

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RADIOACTIVE SEED IMPLANTS

Background

This invention relates to therapeutic radiation treatment and to an improved method of manufacture of radioactive seed implants.

Radioactive pellets or "seeds" have been used to treat a variety of medical conditions, such as cancerous tumors, e.g., in the prostate gland, for many years. These seeds are useful for site-specific delivery of radiation therapy, thereby eliminating many of the undesirable side-effects associated with systemic radiation therapy. Such seeds are typically about 4 mm long and 0.8 mm in diameter and emit low-energy x-rays in the 20-40 keV range. The first such seeds utilized iodine-125 (^{125}I) with a 60-day half-life. More recently, palladium-103 (^{103}Pd) with a 17-day half-life has been used.

U.S. Patent 3,351,049 to Lawrence discloses a method of impregnating a carrier body with a radioactive liquid containing iodine-125, palladium-103, cesium-131, xenon-133, or ytterbium-169. After drying, the carrier body is then encapsulated in a welded canister made of a material such as titanium. Kubiatowitz in U.S. Patent 4,323,055 discloses a method of coating radioactive iodine-125 on to the surface of specially prepared X-ray detectable rods, e.g., silver rods. These coated silver rods are then encapsulated within a canister made of a material such as titanium to create a sealed source.

Another method, disclosed by Carden in U.S. Patent 5,405,309 uses cyclotron-produced palladium-103 which is electroplated onto one or more pellets of an electroconductive material, e.g., graphite rods, and subsequently encapsulated in a shell, such as a welded titanium canister. An extensive chemical separation involving radioactive liquids is described for obtaining palladium-103.

Another method disclosed by Coniglione in U.S. Patent 5,713,828 employs a double-walled tubular structure which is hollow along its major axis. This type of

construction is stated to reduce the migration of seeds by affording better attachment to tissue. The hollow, double-walled tube also permits a rod of suture material to be placed through the seed for better linear placement of seeds during the clinical procedure.

Coniglione also discloses a non-radioactive pre-seed in which a precursor isotope is plated or otherwise coated onto a substrate prior to neutron activation. This technique cannot produce iodine-125 seeds, because the precursor isotope for iodine-125 is xenon-124, an inert gas which cannot be plated or otherwise coated onto a substrate. In addition, for a palladium-103 seed, the method of Coniglione for fabricating a non-radioactive pre-seed generally requires electroplating isotopically pure palladium-102 onto a substrate. A natural distribution of palladium isotopes cannot be used because the presence of palladium-106 would produce a long-lived contaminant radiation. This radiation would be unacceptable because it would expose the patient to unwanted gamma radiation. Such high purity enriched palladium-102 must be purchased from, for example, Oak Ridge National Laboratories or other commercial suppliers at high cost. Palladium-102 enriched to 78 atomic percent is available from Oak Ridge at a price of about $868,000 per gram.

In addition, these enriched isotopes cannot be electroplated on non-conductor substrates such as silicon or plastics. Coniglione teaches that these non-conductive substrates must first be metallized prior to plating with the enriched isotope.

All of the abovementioned technologies have the disadvantage that one must either work with highly radioactive liquids, requiring a high level of skill, substantial expense, and significant risk, or else use a physical coating or electroplating technique to form the radioactive precursor or radioactive layer on a carrier body.

Summary of the Invention

The present invention circumvents the use of radioactive liquids and the need

for coating or electroplating techniques by using mass-analyzed ion implantation both to separate the desired single isotope from other isotopes of the element and to embed the desired isotope into the surface of a substrate. This technique requires only a single piece of equipment under a common vacuum. In addition, the process uses naturally occurring elements, rather than enriched isotopes, as starting materials, and the chosen isotope can be embedded into any material, including metals, ceramics, and polymers.

In one aspect of this invention, an ion implanter is used to produce a single isotope beam and to implant this single isotope below the surface of a carrier body. The ion implanter may use natural elements, such as naturally occurring xenon, barium, palladium, or ytterbium, in its ion source. More than one isotope may be implanted sequentially into the same carrier body. One or more isotopes implanted below the surface of the carrier body may later be activated, e.g., in a nuclear reactor, to form a single radioisotope.

The carrier body may comprise a portion of a device, e.g., a seed or pellet which, when rendered radioactive, may be useful in radiation therapy. The carrier body may be placed inside a sealed titanium cannister or otherwise encapsulated with a titanium coating. The carrier body may be encapsulated prior to activating the precursor isotope embedded in the carrier body.

A coating of biocompatible material, e.g., titanium, carbon, or some combination or variation thereof, may be applied on the surface of the carrier body. The coating of biocompatible material may be between approximately 0.5 microns and approximately 20 microns thick, including all subranges within this range of thickness, depending on the composition of the materials used and the radiation dosage desired for the targeted tissue.

One embodiment of the present invention comprises a non-radioactive pre-seed implant comprising at least one carrier body having a surface, and at least one stable isotope ion-implanted substantially beneath the surface of the carrier body. A plurality of carrier bodies may be included in the implant, if so desired.

The stable isotope for the pre-seed implant may comprise any stable isotope which can be activated to generate a radioactive isotope useful for therapeutic purposes. Such stable isotopes include, for example, palladium-102, xenon-124, barium-130, or ytterbium-168, or a combination or variation thereof. The carrier body of the pre-seed implant may comprise any suitable material, for example, a metal, ceramic, polymer, or combination thereof, which does not become substantially radioactive during exposure to a source of thermal neutrons. Exemplary materials which can be used comprise titanium, titanium dioxide, silicon, silicon dioxide, alumina, copper, rhodium, or some combination or variation thereof, including varying degrees of purity as well as combinations with other materials.

The pre-seed implant may also include one or more radiopaque pellets, which may be formed of a material that does not activate under thermal neutron bombardment, such as, for example, rhodium, gallium arsenide, copper, lead, or some combination or variation thereof.

A non-radioactive pre-seed implant may include a carrier body having an inside surface and an outside surface, and at least one stable isotope ion-implanted substantially beneath the inside surface of the carrier body.

The pre-seed implant may be prepared by a method comprising forming at least one carrier body of a material that does not become substantially radioactive under thermal neutron bombardment and ion-implanting a stable isotope beneath the surface of the carrier body. Ion-implanting the stable isotope may include ion-implanting at a dosage between approximately 1×10^{16} ions/cm^2 and approximately

1×10^{19} ions/cm^2, as well as all subranges and variations of this dosage. Stable isotopes suitable for ion-implantation may include palladium-102, xenon-124, barium-130, ytterbium-168, or some combination or variation thereof.

The method of preparing a pre-seed implant may further include the acts of applying a coating of biocompatible material on the surface of the carrier body, e.g., by a sputtering process, and may involve applying a coating of biocompatible material to the carrier body during or after ion implantation. Such a method may further include encapsulating one or more of the carrier bodies and, optionally, a radiopaque pellet within a titanium canister and sealing the canister shut. Sealing may be effected by any convenient method, for example, by welding.

Another embodiment of the present invention comprises a radioactive seed implant comprising at least one carrier body having a surface; and at least one radioactive isotope embedded substantially beneath the surface of the carrier body. The radioisotope may be any therapeutically effective radioactive material. Preferred radioisotopes comprise, for example, palladium-103, iodine-125, cesium-131, ytterbium-169, or a combination thereof. The carrier body may comprise any suitable material, for example, a metal, ceramic, polymer, or combination thereof, which does not become substantially radioactive during exposure to a source of thermal neutrons. Exemplary materials which can be used comprise aluminum, titanium, titanium dioxide, silicon, silicon dioxide, alumina, copper, rhodium, or some combination or variation thereof. One or more radiopaque pellets or wires may be used in the seed implant so that the location of the implant may be visualized by x-ray techniques.

In another embodiment, the radioactive seed implant may comprise a canister having two ends and an opening at each end, a pair of carrier bodies having an inside surface and an outside surface, and at least one radioactive isotope embedded substantially beneath the inside surface of the carrier bodies, wherein the inside surface of each of the carrier bodies is received within each of the openings

in the canister. Optionally, a radiopaque pellet or wire may be disposed within the canister.

The present radioactive seed implant may be prepared by a method comprising the acts of forming at least one carrier body of a material that does not become substantially radioactive under thermal neutron bombardment, ion-implanting at least one stable isotope into the surface of the carrier body, and exposing the stable isotope to neutron irradiation produce therapeutic quantities of a radioisotope. Such a method may further include placing the carrier body into a titanium canister, and sealing the canister, for example, by welding one or more titanium end-caps on the titanium canister to form a sealed container. Optionally, the method may further include placing at least one pellet or wire of a radiopaque material into the titanium canister. The act of exposing the stable isotope to neutron irradiation may comprise thermal neutron-activating the stable isotope at a dosage between approximately 1×10^{17} neutrons/cm^2 and 1×10^{20} neutrons/cm^2, or between any of the subranges and variations of such dosage. In another aspect, the stable isotope may be exposed to neutron irradiation by neutron-activating the sealed container to produce therapeutic quantities of palladium-103, iodine-125, cesium-131, ytterbium-169, or some combination or variation thereof.

Another method of preparing a radioactive seed implant comprises providing at least one carrier body and ion-implanting at least one radioactive isotope into the surface of the carrier body. The method further may comprise placing the carrier body into a titanium canister, and sealing the canister, for example, by welding one or more titanium end-caps on the titanium canister to form a sealed container. Optionally the method may further comprise placing at least one pellet of a radiopaque material into the titanium canister. Suitable radioactive isotopes include palladium-103, iodine-125, cesium-131, ytterbium-169, or some combination or variation thereof.

The invention further comprises a method of treatment of a cancerous tumor by exposing the tumor to a radioactive implant made according to the present invention. For example, a radioactive implant prepared as described above may be placed in an area of tissue affected by the tumor, thereby permitting a therapeutic dosage of radiation to be delivered to the cancerous tumor.

Brief Description Of Drawings

FIG. 1 schematically illustrates a mass-analyzed ion implantation apparatus used to embed the single precursor isotope into the carrier bodies.

FIG. 2 illustrates a cross-sectional view of a radioactive seed implant according to one embodiment of the present invention wherein two radioactive seeds are separated by a radiopaque pellet.

FIG. 3 illustrates an alternative embodiment of a radioactive seed implant using a single ion-implanted carrier body coated with a sealant metal.

FIG. 4 illustrates a further alternative embodiment of a radioactive seed implant wherein the endcaps also serve as the ion-implanted carrier bodies.

FIG. 5 illustrates another alternative embodiment of a radioactive seed implant wherein a single tube is implanted with the precursor isotope thereby obviating the need for welding.

Detailed Description of the Preferred Embodiments

The present invention comprises radioactive therapeutic devices, such as radioactive seed implants, and methods for preparing them. Radioactive isotopes or non-radioactive precursor isotopes are implanted into a carrier body using ion implantation. Ion implantation preferably is carried out using a mass-analyzed ion

implanter, which both separates the desired isotope of an element from a sample of an element and implants the desired isotope into the carrier body.

The ability of the mass-analyzed ion implanter to separate a particular isotope from a sample of an element obviates the need for purchasing an expensive, isotopically pure sample of an element, e.g., palladium-102. Furthermore, because the separation and implantation of isotopes may be carried out in a single chamber, no special handling of radioactive elements is required and no tedious separations of radioactive isotopes are needed, as would be necessary for coating a carrier body with a radioactive isotope using existing plating and coating techniques.

In addition, this technique permits the use of volatile precursor elements, e.g., xenon-124, which cannot be employed in traditional plating and coating techniques. In this manner, a carrier body including a radioactive isotope derived from a volatile precursor element, e.g., iodine-125, can be prepared without performing a coating step using the radioactive element itself.

FIG. 1 of the drawings illustrates schematically an ion implantation apparatus that can be used to embed single isotopes into carrier bodies for the preferred embodiments of the invention. In this apparatus, a confined plasma 11 of the element containing the specific isotope to be implanted is created within an ion source 12. The positive ions are extracted by a set of electrodes 13 and accelerated into a mass-analyzing magnet 14. The magnet separates the isotopes into beams according to the mass of the ions, and the specific isotope beam may then be focused and passed through a mass selection slit 15. The ion beam may then be raster scanned in the horizontal and vertical directions by a set of scanner plates 16 and directed onto an array of carrier bodies 17, which may be held on a rotating platform 18. All of the elements of this apparatus may be contained within a single vacuum, represented by chamber 19. The ion beam of the specific isotope may be accelerated to high energies, e.g., 200 keV, sufficient to embed these isotope atoms up to 0.2 microns deep into the carrier bodies. The carrier bodies, which may be

cylindrical in shape, may be rotated and tilted at a 45° angle to the beam to uniformly implant the outside surfaces and to prevent shadowing of one carrier body by the others.

Ion implantation may be accomplished using a high-current ion implanter such as is presently widely used in the semiconductor industry for doping silicon electronic devices. For example, Eaton model NV-GSD or Varian model 180XP having beam currents in excess of 20 milliamperes can be used. The ion implanter should have sufficient beam current capability and mass resolution to generate at least a few microamps of the desired isotope. For example, naturally occurring xenon has nine isotopes ranging in mass from 124 to 136. Xenon-124, however, only has a relative abundance of 0.1%. A ten milliamp capability implanter would yield ten
microamps of xenon-124.

Typical beam currents for xenon-124, for example, may be ten to twenty microamps. For a typical array of carrier bodies consisting of 1600 pieces mounted on a three-inch diameter plate, the implantation time would be twenty-five to fifty hours per batch.

FIG. 2 of the drawings illustrates one of the preferred embodiments of the devices and methods disclosed herein. In FIG. 2, two carrier bodies 100a and 100b at each end of the seed are made of an appropriate low atomic number, low density material, and are surface-implanted 30 with the lowest weight isotope of xenon, palladium, barium, or ytterbium using a high current ion implanter. Lowest weight isotopes for these elements are xenon-124, palladium-102, barium-130, and ytterbium-168, respectively. Any isotope that can be activated by neutron activation may be ion-implanted into the surface.

Preferred isotopes for implantation should be chosen to be essentially free of alpha and beta emissions after activation, and should have greater than 95% of their radiation in low energy X-rays of energy less than 100 thousand electron volts (keV).

Upon activation, xenon-124 becomes xenon-125 which has a 17.1 hour half-life, and quickly beta-decays to iodine-125. Iodine-125 is desirable because it is in widespread use and can be beneficial for the treatment of early stages of prostate cancer. Ytterbium-169 may be useful for both early, middle, and late stages of prostate cancer. Palladium-103 may be useful for more advanced stages of prostate cancer or for more aggressive forms of cancer. The usefulness of a radioisotope for a particular type of cancer or a particular stage of cancer is generally related to the half-life of the radioisotope and the total dose, and is apparent to those of skill in the art.

There will generally be some absorption of the radiation by the encapsulation material 20, and such absorption will tend to diminish the amount of radiation delivered to the tissue to be treated. Thus, the desired radiation dosage amount and the attenuation factor may be considered in determining the quantity and type of isotope to be used. In addition, the amount of absorption generally will be related to the thickness of the capsule walls 20, which preferably should be thick enough to impart sufficient mechanical strength to the seed. Preferably, the capsule material 20 should be selected from low atomic number materials, for example, with an atomic number in the range of about 4 to about 28 inclusive. The capsule material 20 preferably may be corrosion resistant, compatible with body tissue, and nontoxic. Alternatively, the capsule may have a coating with these characteristics.

An appropriate low density, low atomic number carrier body 100a, 100b may be made of single-crystal silicon. Alternatively, the carrier body could be a combination, e.g., a coating of titanium or silicon applied to a silica or alumina substrate.

Single-crystal semiconductor grade silicon is a preferred material because it does not contain contaminants that will activate significantly in a nuclear reactor. Semiconductor grade silicon is one of the purest substances made by man, containing less than one part per billion of neutron-activatable elements. In an appropriate vacuum chamber, the isotopically pure ion beam may directed on the silicon carrier body using a kinetic energy of approximately 20 to approximately 200 keV for a duration sufficient to ion implant between approximately 1 x 10^{17} and approximately 1 x 10^{18} ions/cm^2 on substantially all surfaces of the pellet. At 200 keV, the ions penetrate up to approximately 2,000 angstroms into the silicon surface.

After implantation, the pellets are placed in a high flux nuclear reactor, such as the University of Missouri Research Reactor, at a flux rate of approximately 8 x 10^{13} neutrons/cm^2/sec.

After activation, two pellets 100a, 100b, and a lead, gold, or tungsten pellet 40, may be placed in a titanium tube 20, with a pair of end caps 50a, 50b, as shown in FIG. 2, and the end caps are laser-welded to form a sealed "seed". Sealing the seed prevents migration of the radioisotope and preferably should not have radiation shielding properties. Optionally, the tube may be made from titanium combined with another material, e.g., aluminum.

In the preceding practice, the silicon carrier bodies 100a, 100b, were placed in the reactor and consequently, the assembly and laser welding must be performed on a radioactive assembly.

Alternately, if sufficiently pure titanium and radiopaque marker material can be manufactured, it is possible to prepare and weld the assembly before placing the assembly in the nuclear reactor for activation. Titanium is preferred for encapsulation because it is a very biocompatible material and does not neutron activate to include a significant quantity of radioisotopes with long half-lives.

Moreover, titanium may be obtained in very pure form, e.g., 99.999% purity. Care must be taken to ensure that any remaining impurities do not activate to long half-life radioisotopes.

Referring to FIG. 3, this alternative approach uses a carrier body 100 made of ultra pure copper, rhodium, or other high atomic number, high density element or compound which does not produce a significant quantity of long-lived radioisotopes under neutron bombardment. Copper, for example, has two stable isotopes, ^{63}Cu and ^{64}Cu which neutron activate to ^{64}Cu and ^{66}Cu respectively. These two radioisotopes have half-lives of twelve hours and five minutes respectively and may decay to zero before the seed is implanted into a patient. Similarly rhodium has no long-lived neutron activation products. The carrier material may be chosen to facilitate working in the small dimensions desired for the seed implant.

Copper also is desirable because it is available in purities of 99.999% (Alpha Chemicals) and in wire form. Care must be taken, however, to ensure that the remaining impurities do not activate to long half-life radioisotopes. Iron, cobalt, zinc, and manganese contaminants preferably should be avoided. Similarly, rhodium preferably should be free of platinum and iridium contaminants.

A sufficiently pure carrier body 100 may be ion-implanted with one of the four aforementioned pure isotopes 31 to a dose of approximately 1×10^{16} to approximately 1×10^{18} atoms/cm^2. In this embodiment, there should preferably be a simultaneous deposition of titanium on the carrier body 100 to lower the sputtering rate of the carrier body material due to the impingement of the ion beam. Alternatively, one could alternate the ion implant and titanium sputter coating, e.g., for approximately five times, while implanting the full required dose. After ion implantation, the seed could optionally be sputter-coated with ultra-pure titanium 21, to a thickness of approximately ten microns to approximately twenty microns, using magnetron sputtering to further encapsulate the seed.

The assembly may then be placed in a nuclear reactor to generate the desired radioactivity.

The shape of the radioactive seed implant preferably is rounded so that the radiation distribution is spherical at each end, thereby making the implant more similar to a uniform point source. However, any shape, such as a more square shape, may be used instead.

FIG. 4 shows an exploded view of an additional alternate embodiment wherein two end caps 51a, 51b are also carrier bodies for the ion-implanted isotope 32. When the two end caps 51a, 51b are inserted and welded, they also serve to center and pin the radiopaque marker 40 in place within the tube 20.

Fig. 5 shows yet another alternate embodiment wherein a single titanium tube is used as a carrier body 22. The stable precursor isotope 33 may be ion-implanted into the surface of the carrier body 22 which can then, either simultaneously or after ion implantation, be sputter-coated with pure titanium to provide additional sealant for the radioactivity after the carrier body is activated in a nuclear reactor. After activation, a radiopaque pellet 42 may be placed in the center of the tube. Since the radiopaque pellet is placed in the tube after activation, the pellet need not be made of a non-activatable material and is preferably made of gold. Using gold, for example, the pellet may be squeezed from both flat sides to cause it to bulge radially and thus be substantially permanently fixed in the tube.

This embodiment most clearly illustrates the advantages of ion implantation of the precursor isotope over other methods of coating, such as electroplating or physical vapor deposition. With ion implantation, there is no need for a double-walled tube to encapsulate the radioisotope, as taught by Coniglione. A hollow tube structure can be made and sealed using a single tube construction.

The following examples are included to further illustrate the invention for three specific radioisotopes, but are to be considered as exemplary only and not as limiting the invention in any way.

Example #1

The following example illustrates the process of making a radioactive seed containing ^{125}I according to the embodiment of Fig. 3.

carrier body:	99.999% pure copper
size:	0.75 mm dia., 4 mm long, spherical ends
surface area:	0.08 cm^2
^{124}Xe implant dose:	1 x 10^{17} atoms/cm^2
ion implant energy:	200 keV
^{124}Xe atoms in surface:	8 x 10^{15} atoms
sputter coat of titanium:	1 micron thick
neutron dose rate:	8 x 10^{13} neutrons/cm^2/sec
neutron dose duration:	290 hrs
initial ^{125}I activity:	0.4 millicurie
photon equiv. activity:	0.6 millicurie

Eighteen days after removal from the nuclear reactor, which allows adequate time for total radioactivity measurement, certification, and sterilization, the seed will have decayed to 0.5 millicurie and will be ready to implant into a diseased prostate gland. At a 0.5 millicurie source strength, approximately 160 Grays absorbed dose will be given to the tumor surrounding an array of 80 to 100 seeds properly spaced within the prostate gland.

Example #2

The following example illustrates the process of making a radioactive seed containing ^{103}Pd according to the embodiment of Figure 5.

carrier body:	99.999% pure titanium tube
size:	0.81 mm dia., 4.5 mm long
surface area:	0.115 cm^2
^{102}Pd implant dose:	2 x $10^{18}/cm^2$
ion implant energy:	200 keV
^{102}Pd atoms in surface:	2.30 x 10^{17}
sputter coat of titanium:	1 micron thick
neutron dose rate:	8 x 10^{13} neutrons/cm^2/sec
neutron dose duration:	522 hrs
initial ^{103}Pd activity:	1.3 mCi
photon equiv. activity:	1.0 mCi

One millicurie of ^{103}Pd will produce approximately 160 Grays at a tumor site.

Example #3

The following example illustrates the process of making a radioactive seed implant containing ^{169}Yb according to an embodiment of Fig. 2.

carrier bodies:	semiconductor silicon (2 pieces)
size:	0.6 mm x 0.6 mm x 1 mm each
surface area:	0.048 cm^2 (for 2 pieces)
^{168}Yb implant dose:	1 x $10^{16}/cm^2$
ion implant energy:	200 keV

^{168}Yb atoms on surface:	1.15×10^{15}
sputter coat of titanium:	1 micron thick
neutron dose rate:	8×10^{13} neutrons/cm^2/sec
neutron dose duration:	143 hrs
Initial ^{169}Yb activity:	0.5 mCi
photon equiv. activity:	1.1 mCi (between 50-63 keV x-rays)

At this seed activity, the dose at the tumor site is approximately the useful therapeutic dose of 160 Grays for an array of 80-100 seeds.

While the invention has been disclosed in connection with the preferred embodiments shown and described in detail, various modifications and improvements will be apparent to one of ordinary skill in the art from the above description. For example, and without limitation, it may be beneficial to ion implant two or more different stable isotopes prior to activation. For example, it may be useful to employ both ytterbium and iodine, thereby yielding a higher radiation dose to the patient in the short term which levels off to a slower dose rate in the longer term. The proportion of each isotope used could be determined based on the therapeutic effects desired for the patient.

Claims

1. A radioactive seed implant, comprising:

at least one carrier body having a surface; and

at least one radioactive isotope selected from the group consisting of palladium-103, iodine-125, cesium-131, and ytterbium-169 embedded substantially beneath the surface of said carrier body.

2. The radioactive seed implant of claim 1, wherein the radioactive isotope is ion-implanted.

3. The radioactive seed implant of claim 1, further comprising a shell of biocompatible material encapsulating said carrier body.

4. The radioactive seed implant of claim 1, wherein said carrier body comprises a material selected from the group consisting of aluminum, titanium, titanium dioxide, silicon, silicon dioxide, alumina, copper and rhodium.

5. The radioactive seed implant of claim 1, wherein said carrier body comprises at least two materials selected from the group consisting of aluminum, titanium, titanium dioxide, silicon, silicon dioxide, alumina, copper and rhodium.

6. A pre-seed implant, comprising:

at least one carrier body having a surface; and

at least one stable isotope selected from the group consisting of palladium-102, xenon-124, barium-130, and ytterbium-168 embedded substantially beneath the surface of said carrier body.

7. The pre-seed implant of claim 6, wherein the radioactive isotope is ion-implanted.

8. The pre-seed implant of claim 6, wherein said carrier body comprises at least one material selected from the group consisting of aluminum, titanium, titanium dioxide, silicon, silicon dioxide, alumina, copper and rhodium.

9. The pre-seed implant of claim 6, further comprising a radiopaque pellet formed of a material that does not activate under thermal neutron bombardment.

10. The pre-seed implant of claim 6, further comprising a radiopaque pellet including at least one material selected from the group consisting of rhodium, gallium arsenide, and copper.

11. The pre-seed implant of claim 8, further comprising a canister surrounding said radiopaque pellet and said carrier body.

12. The pre-seed implant of claim 11, wherein said canister comprises titanium.

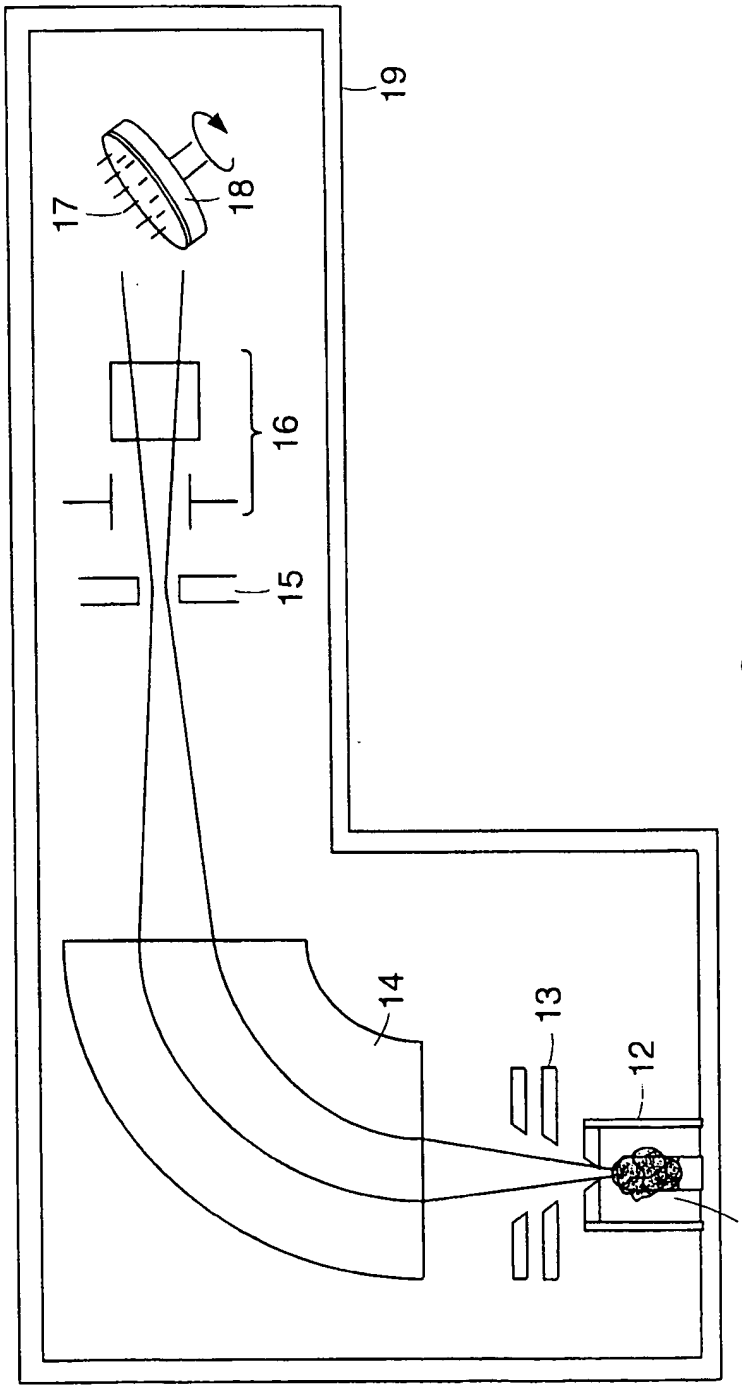

FIG. 1

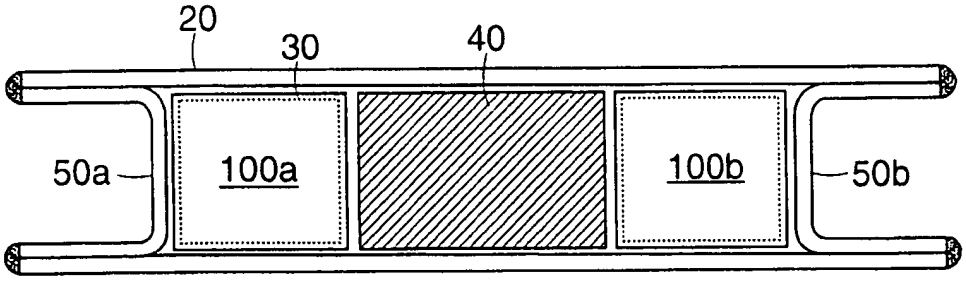

FIG. 2

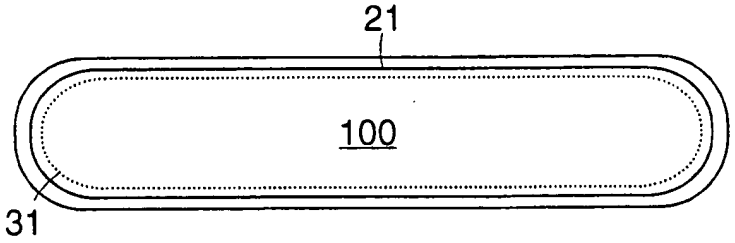

FIG. 3

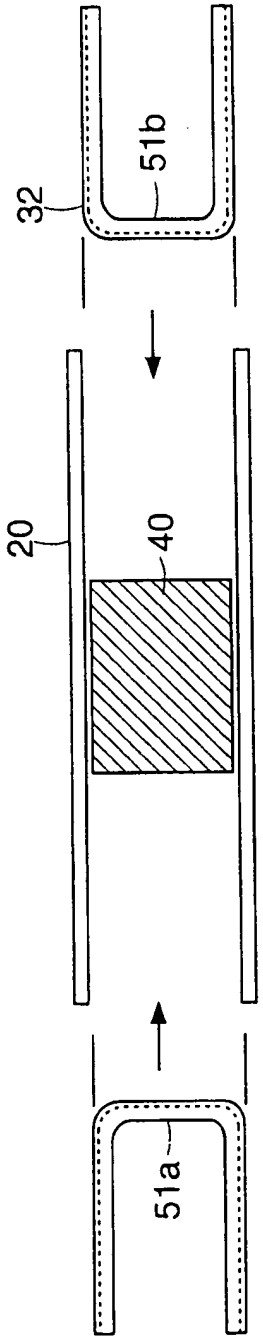

FIG. 4

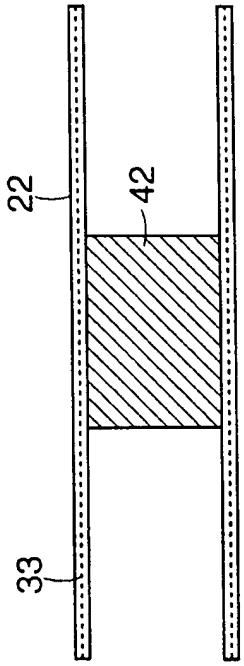

FIG. 5